IMPLICATIONS OF THE GIANT PLANETS FOR THE FORMATION AND EVOLUTION OF PLANETARY SYSTEMS

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Abstract. The giant planet region in our Solar System appears to be bounded inside by the limit of water condensation, suggesting that the most abundant astrophysical condensate plays an important role in giant planet formation. Indeed, Jupiter and Saturn exhibit evidence for rock and/or ice cores or central concentrations that probably accumulated first, acting as nuclei for subsequent gas accumulation. This is a "planetary" accumulation process, distinct from the stellar formation process, even though most of Jupiter has a similar composition to the primordial Sun. Uranus and Neptune are more complicated and imperfectly understood, but appear to exhibit evidence of an important role for giant impacts in their structure and evolution. Despite some interesting systematics among the four major planets and their satellites, no simple picture emerges for the temperature structure of the solar nebula from observations alone. However, it seems likely that Jupiter is the key to our planetary system and a similar planet could be expected for other systems. The data and inferences of these data are summarized for the entire known Solar System beyond the asteroid belt.

1. INTRODUCTION

In our Solar System, over 99.5% of the known planetary mass resides in the planets beyond the asteroid belt, primarily in Jupiter, Saturn, Uranus, and Neptune. From the point of view of an earthbound cosmochemist, these bodies are not a "well known" (*i.e.*, sampled) part of the Solar System, but from the point of view of the astronomer or anyone seeking a general understanding of planetary system detectability and taxonomy, the giant planets should be the most important source of information. Of course, we cannot assess (yet) whether our planetary distribution and characteristics are typical, but we can at least use our developing understanding of our Solar System to establish generalizing postulates and testable conjectures concerning other systems. In this contribution, I provide a summary of what is known, as well as a (more personal) assessment of what it means.

2. THE MASS DISTRIBUTION

It is convenient to divide the constituents of planets into three components: "gas" (primarily hydrogen and helium; not condensible as liquid or solid under Solar System conditions), "ices" (volatile but condensible to varying degrees; H_2O is the most common, CO, CH_4, NH_3, and N_2 are the other main ones), and "rock" (essentially everything else; primarily silicates and metallic or oxidized iron).

Jupiter defines a remarkable transition in our planetary system. Inside of Jupiter's orbit at 5 AU, the planets are small and rocky, largely devoid of both "ices" (especially water, the most abundant condensate in the universe) and "gas." By contrast, Jupiter has about three hundred Earth masses of gas, and the more distant giant planets, though less well endowed, also have large reservoirs of gas. It is perhaps even more significant that Jupiter is the first place outward from the Sun at which water ice appears to become a common condensate. Although we do not know the abundance of water in Jupiter (because it forms clouds deep in the atmosphere), we see satellites such as Ganymede and Callisto which contain about as much ice as rock by mass, and we observe enhancements of other "ices" (CH_4 and NH_3) in the Jovian atmosphere. The reason why this may be so significant will emerge in several ways during the subsequent discussion. For now, it suffices to note that interior models for Jupiter and Saturn (discussed in the next section) reveal the need for dense cores or central concentrations of ice and/or rock of order ten or so Earth masses and it is likely that these cores were the nucleating "seeds" for gas accumulation. It will be argued that the large mass of gas in Jupiter is the *consequence* of a suitable nucleation center, which arose in turn because of water condensation.

The outer edge of the Solar System is ill-defined. It is possible that the cometary cloud contains a greater amount of ice and rock than do all the giant planets combined, especially if the most massive comets are substantially larger than the comets we have seen. A more conservative estimate of total cometary mass is $\sim$ ten earth masses, but with a very large uncertainty (*e.g.*, Duncan, Quinn, and Tremaine 1987). Some increase in this estimate is justified given the recent realization that Halley is more massive than previously suspected (Sagdeev, Elyasberg, and Moroz 1988). The inner part of the cometary distribution, sometimes called the Kuiper belt, has now been tentatively identified as a disk rather than a spherical cloud (Duncan, Quinn, and Tremaine 1988) and is therefore clearly associated with the planetary formation process. Planet X (a body beyond Pluto) has been frequently mentioned as a possibility, and no firm evidence currently exists for or against. There is sometimes a tendency to adopt an anthropocentric viewpoint in discussions of the Solar System, in which inner Solar System observations (including meteorites) play an important role in the conceptual development; but, it is important to remember that most of the Solar System condensate resides at enormous distances.

One game that can be played is called *reconstituting the nebula*. One looks at the estimated amounts of rock and ice in each of the giant planets, then asks how much material of cosmic composition would be required to provide that much rock and ice. Roughly speaking, this implies that each of the four major planets required $\sim 0.01\ M_\odot$ of cosmic composition material. The cometary reservoir may have required an amount comparable to each of the planets. The similarity for each giant planet arises because they have roughly similar amounts of ice and rock (10–20 Earth masses) but diminishing amounts of gas as one proceeds outwards. The planets are also spaced in orbits that define a roughly geometric progression. In other words,

$$0.01\, M_{\odot} \simeq \int_{R}^{2R} \sigma(R')\, 2\pi R' dR' \tag{1}$$

independent of R, where $\sigma(R)$ is the "surface density" (mass per unit area) of the discoid nebula from which the planets form, and R is the (cylindrical) radius. This implies $\sigma(R) \sim (2 \times 10^4 \text{ g cm}^{-2})/R^2$ where R is in astronomical units. Theoretical models for $\sigma(R)$ from accretion disk theory tend to give somewhat weaker dependences on R, implying a stronger tendency for most of the mass to be near the outer limits of the nebula. Naturally, most of the angular momentum is also concentrated in the outer extremities. The outer radius of the solar nebula is not known, but was presumably determined by the angular momentum budget of the cloud from which the Sun and planets formed.

3. INTERIOR MODELS

We could say a lot about how giant planets formed if we knew their internal structures. However, we have no techniques (yet) that are similar to terrestrial or solar seismology and which enables us to "invert" for the interior densities in a detailed way. Instead, we must rely on a very small set of data, the lower-order (hydrostatic) gravitational moments, and the number of confident statements regarding the interiors is correspondingly small. Even if the *quantity* of information thus obtained is low, the *quality* is high and represents a quite large investment of theoretical and computational effort, together with some important experimental data from high pressure physics. Although the theory is not always simple, its reliability is believed to be high. The great danger exists, however, in overinterpreting the very limited data.

Good reviews on the structure of giant planets include Zharkov and Trubitsyn (1978), Stevenson (1982), and Hubbard (1984) and it is unnecessary to repeat here the techniques, data, and procedures used. In the case of Jupiter, there is no doubt that $\sim$ 90–95% of the total mass can be approximated as "cosmic" composition (meaning primordial solar composition). However, the gravitational moment J_2 (which can be thought of as a measure of the moment of inertia) indicates that there must be some central concentration of more dense material (ice and rock). A typical acceptable model is displayed in Figure 1. The uncertainties in hydrogen and helium equations of state are not sufficient to attribute this central density "excess" to an anomalously large compressibility of H–He mixtures or even to a helium core (since the latter can be limited in size by the observational constraints on depletion of helium in the outer regions of the planet). There is no way to tell what the "core" composition is; it could be all rock or all ice or any mixture in between. It does not even need to be a distinct core; only a substantial enhancement of ice and/or rock in the innermost regions. The amount of such material might be as little as five Earth masses but is probably in the range of 10–30 Earth masses. The upper range of estimates is most reasonable if a substantial portion of this heavy material is mixed upward into the hydrogen and helium. One important point for the purposes of understanding its origin is that Jupiter is enhanced in rock and ice by roughly a factor of ten relative to cosmic composition. In other words, Jupiter formed from a cosmic reservoir containing $10^{-2}\, M_{\odot}$, even though its final mass is only $10^{-3}\ M_\odot$, a fact we had already noted in the previous section. The other important point about the dense material is the following: it probably did not accumulate near the center by rainout of insoluble matter. This is in striking contrast to the Earth's core which formed because metallic iron was *both* more dense and insoluble in the mantle (silicates and oxides). The temperature in the center of Jupiter is very high ($\gtrsim 20{,}000$ K) and the mole fraction of the ice or rock phases, were they mixed uniformly in hydrogen, would not exceed 10^{-2}. Although solubility calculations are difficult (see Stevenson 1985), there does not seem to be any likelihood that some component would be insoluble at the level of 10^{-2} mole fraction at $T \sim 20{,}000$ K, since this requires an excess Gibbs energy of mixing of order $kT \ln 100 \sim 8$ eV, well in excess of any electronic estimate based on pseudo-potential theory. It seems likely that Jupiter formed by first accumulating a dense core; the gas was added later. Subsequent convective "dredging" was insufficient to homogenize the planet (Stevenson 1985).

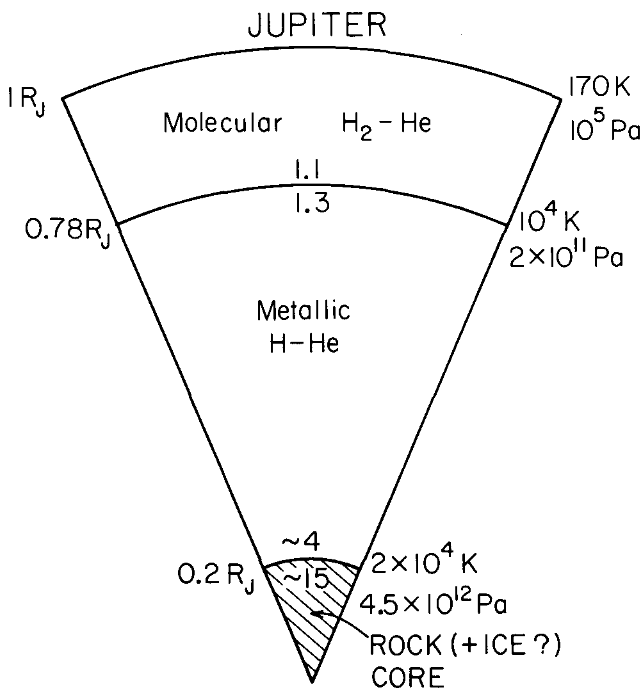

Figure 1. *Possible structure of Jupiter. Boundaries are labeled by densities (in* g cm^{-3}*) and pressures are given in Pascals (*10^5 *Pa* $\equiv$ *1 bar).*

Saturn is further removed from a simple cosmic composition than Jupiter, a fact that can be deduced from the density alone since a body with the same composition as Jupiter but the same mass as Saturn would have about the same *radius* as Jupiter (Stevenson 1982). Saturn has only 83% of Jupiter's radius implying a dense core that causes contraction of the overlying hydrogen–helium envelope. In fact, the ice and rock core of Saturn has a similar mass to that of Jupiter, but this is a larger fraction of the total mass in the case of Saturn. An additional complication in Saturn's evolution arises because of the limited solubility of helium in metallic hydrogen, predicted long ago but now verified by atmospheric abundance measurements. A likely structure for Saturn is shown in Figure 2. The presence of a helium-rich deep region is compatible with the gravity field (Gudkova, Zharkov, and Leontiev 1988) as well as being required by mass balance considerations. As with Jupiter, the ice and rock central concentration must be primordial and formed the nucleus for subsequent accretion of gas.

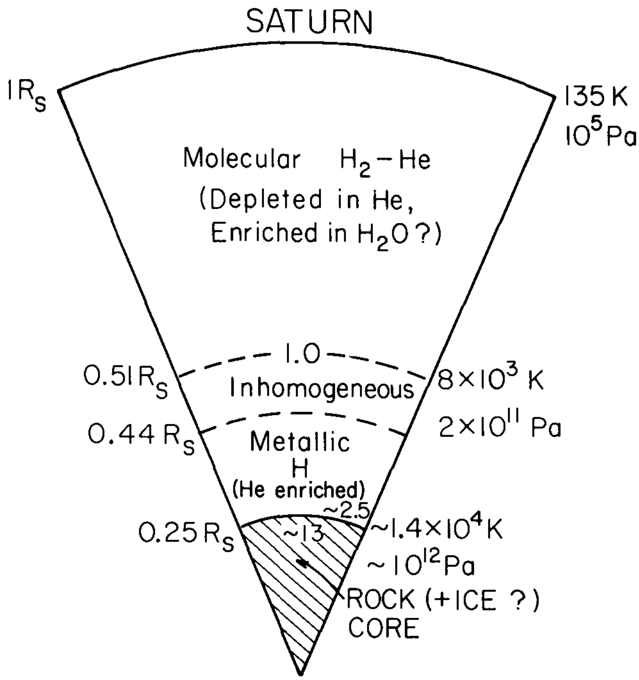

Figure 2. *Possible structure of Saturn; same notation as for Jupiter. Dashed boundaries imply gradual changes.*

Despite recent accurate gravity field information (French *et al.* 1988) based on ring occultations, models for Uranus are not yet so well characterized. The problem lies not with the general features of the density structure but with the interpretation of this structure, since no particular component (gas, ice, or rock) has predominance. A mixture of gas and rock can behave like ice, leading to a considerable ambiguity of interpretation. There is no doubt that the outermost $\sim$ 20% in radius is mostly gas and it is generally conceded that some rock is present within Uranus (though not much in a separate, central core). It is clear that the models require some mixing among the constituents: it is not possible to have a model consisting of a rock core with an ice shell and an overlying gas envelope as suggested around 1980. It is not even possible to have a model consisting of a rock core and a uniformly mixed envelope of ice and gas. The most likely model seems to involve a gradational mixing of constituents, although with rock still primarily concentrated toward the center and gas still primarily concentrated toward the outside. This is illustrated schematically in Figure 3.

Accurate models of Neptune must await the flyby in August, 1989. Based on the existing, approximate information it seems likely that the main difference between Uranus and Neptune is the extent of mixing of the constituents. Uranus has a substantial degree of central concentration (low moment of inertia), despite the inference of mixing

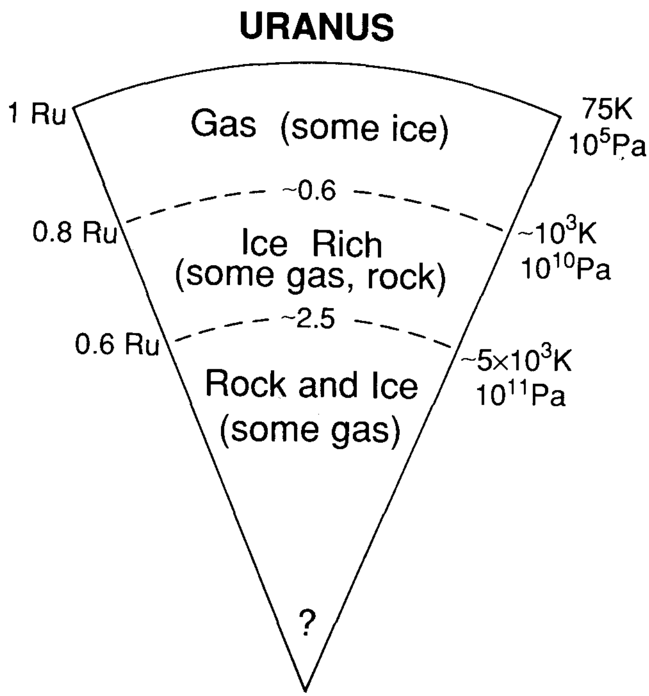

Figure 3. *Possible structure of Uranus; unlike Jupiter and Saturn, there are no clear distinctions among the various regions. Densities and temperatures are poorly determined.*

described above. Neptune has a higher moment of inertia, suggesting far greater homogenization. At the high temperatures ($\sim 10^4$ K) and pressures (0.1 Mbar and above) of this mixing, phase separation is unlikely to occur, so the degree of homogenization may reflect the formation process (degree of impact stirring) rather than the phase diagram. In Section 5, I describe a speculative interpretation of the differences between Uranus and Neptune.

4. ATMOSPHERIC COMPOSITIONS AND THEIR IMPLICATIONS

Many of the minor constituents in giant planets undergo condensation (cloud formation) deep in the atmosphere and their abundances are accordingly not well known. The main exceptions are methane (which either does not condense or condenses in a region accessible to occultation and IR studies) and deuterated hydrogen (HD). Some limited information on other species (especially NH_3) exists from radio observations, for example, but we focus here on carbon and deuterium.

Carbon is enriched relative to cosmic by a factor of 2 in Jupiter, 5 in Saturn, and ~ 20 in Uranus. At least in the cases of Jupiter and Saturn, the enhancement cannot be due to local condensation of the expected carbon–bearing molecules present in the primordial solar nebula (CO or CH_4) even allowing for clathrate formation. This interpretation follows from the fact that water ice did not condense closer to the Sun than about Jupiter's orbit, yet any solid incorporating CO or CH_4 requires a much lower temperature than water to condense (Lewis 1972). The enhancement of carbon must arise either through ingestion of planetesimals containing involatile carbon or "comets" (planetesimals that formed farther out and were scattered into Jupiter-crossing orbits). There is increasing awareness of involatile carbon as a major carbon reservoir in the interstellar medium and it has long been recognized as a significant component of primitive meteorites (*e.g.*, Briggs and Mamikunian 1963). Isotopic evidence suggests that some of this meteoritic organic material has an interstellar origin (Yang and Epstein 1983). Comets also possess a substantial involatile carbon reservoir (Kissel and Kreuger 1987), but much of the cometary carbon reservoir is in C–O bonded material (part but not all as carbon monoxide, Eberhardt *et al.* 1987). If we are to judge from known carbonaceous chondrites then the amount of such material needed to create the observed Jovian or Saturnian carbon enrichment is very large, twenty to thirty Earth masses, especially when one considers that this must be *assimilated* material (not part of the unassimilated core). Comets would be a more "efficient" source of the needed carbon, but it is also possible that the currently known carbonaceous chondrites do not reflect the most carbon–rich (but ice–poor) material in the asteroid belt and beyond. Even with comets, one needs of order ten Earth masses of material added to Jupiter after it has largely accumulated. The implication is that estimates of ice and rock in Jupiter or Saturn, based solely on the gravity field, are likely to be lower than the true value because much of the ice and rock is assimilated (and therefore has no clean gravitational signature). Simonelli *et al.* (1988) present a more detailed discussion of the Solar System carbon budget.

In Jupiter and Saturn, the value of $D/H \sim 2 \times 10^{-5}$ is believed to be "cosmic", although this interpretation is still imperfectly established because of uncertainties in the "cosmic" value, and what this value really means (*i.e.*, is it a primordial, Universal value?). A cosmic value seems like a reasonable expectation, but it must be recognized that there are very strong fractionation processes in the interstellar medium which deplete the gas phase and enrich the particulate material. This enrichment is well documented for meteorites (Yang and Epstein 1983) and is also probably present in comets. It is likely that the gaseous component of proto-Jupiter was *depleted* in deuterium, but that the assimilation of the carbon–bearing solids described above also contributed deuterium–rich materials, probably more than compensating for the gas–phase depletion. Thus, D/H in Jupiter is probably in excess of cosmic, though perhaps not by a large enough factor to be detectable in the current data. In contrast, Uranus is clearly enriched ($D/H \sim 10^{-4}$), an expected result given the far higher ratio of ice or rock to gas in that planet and the evidence of at least partial mixing discussed earlier. Neptune might be expected to have an even larger D/H if it is more substantially mixed than Uranus.

In summary, atmospheric observations provide additional evidence of non-cosmic composition and partial assimilation of "heavy" material (ice and rock) into the envelopes of giant planets.

5. HEAT FLOWS AND THEIR IMPLICATIONS

Jupiter, Saturn, and Neptune emit more energy than they receive from the Sun, implying significant internal energy sources. The *ultimate* source of this energy is undoubtedly gravitational, but there are several ways in which this energy can become available. In Jupiter, the heat flow is consistent with a simple cooling model in which the planet was initially much hotter and has gradually cooled throughout the age of the

Solar System (*e.g.,* Hubbard 1980). In this case, the gravitational energy of accretion created the primordial heat reservoir responsible for the current heat leakage. In Saturn, the heatflow is marginally consistent with the same interpretation, but the observed depletion of helium in the atmosphere requires a large gravitational energy release from the downward migration of helium droplets (Hubbard and Stevenson 1984). This process may also contribute part of the Jovian heatflow. Even with helium rainout, it is necessary to begin the evolution with a hot planet (at least twice as hot as the present interior thermal state), but this constraint is easily satisfied by accretion models.

Uranus and Neptune have strikingly different heatflows. The Uranus internal heat output is less than 6×10^{21} erg s^{-1} and might be zero; expressed as energy output per gram, this is an even *lower luminosity than the Earth.* The Neptune heatflow is about 2×10^{22} erg s^{-1}. Although clearly much larger, it is still *less* than one would expect if Neptune were fully adiabatic and began its evolution with an internal temperature of at least twice its present value (the assumption that works so well for Jupiter). The difference between Uranus and Neptune is striking and not easily explained solely by their different distances from the Sun. It is also unlikely that these planets began "cold" (*i.e.,* only slightly hotter than their present states) since the energy of accretion is enough to heat the interior by $\sim 2 \times 10^4$ K. I propose that the low heat flow of Uranus is due to stored heat of accretion; this heat is unable to escape because of compositional gradients, which inhibit thermal convection. In this way we can reconcile the low heat flow of Uranus with a high heat content and the inferred partial mixing of the interior discussed in Section 3. By contrast, Neptune has a relatively high heatflow because it is more uniformly mixed. A speculative explanation for this difference in mixing efficiency is as follows: the last giant impact on Uranus was oblique and created the large obliquity and disk from which the satellites formed (cf. Cameron 1975; Stevenson 1984a). This impact was not efficient in mixing the deep interior. By contrast, the last giant impact on Neptune was nearly head-on, which is a more efficient way of heating and mixing the interior and did not lead to the formation of a compact, regular satellite system. The high heatflow of Neptune is accordingly related to its higher moment of inertia. This speculation may be testable after the Voyager encounter at Neptune.

In summary, the heatflows of giant planets support the expectation that these planets began their life hot. In some cases (*e.g.,* Jupiter) much of this heat has since leaked out; in at least one case (Uranus) the heat has been stored, prevented from escaping by compositional gradients which inhibit convection.

6. SATELLITE SYSTEMS

The four giant planets exhibit a startling diversity of satellite systems. Jupiter has four large, comparable mass satellites with a systematic variation of density with distance, suggesting a "miniature Solar System." Saturn has an extensive satellite system, though only one of the satellites (Titan) is comparable to a Galilean satellite. Uranus has a compact family of icy satellites, regularly spaced and in the equatorial plane. Neptune has only two known satellites, in irregular orbits. One of these is Triton, a large body that has significant reservoirs of CH_4 and possibly N_2. What can we learn about planetary and Solar System origin from these observations? We learn first that satellites are common and that they probably have diverse origins (Stevenson, Harris, and Lunine 1986). Some of the diversity may arise as the stochastic outcome of a common physical process (this may explain the difference between Jovian and Saturnian systems) but the Neptunian system is clearly different and one suspects that the Uranian system has a different history also, since it formed around a planet that was tipped over and never had as much gas accretion as Jupiter or Saturn. The recent enthusiasm for an impact origin of the Earth's moon (Hartmann, Phillips, and Taylor 1986) suggests that the Uranian system deserves similar attention. Impact origin seems to make less sense for Jupiter and Saturn, where the target is mostly gas, even though these planets must also have had giant impacts. The issue for Neptune is unresolved, though one wonders how a distant, nonequatorial and *inwardly* evolving satellite such as Triton could have an impact origin. Perhaps Triton was captured.

The formation of Jovian and Saturnian satellites is commonly attributed to a disk associated with the planet's formation, and therefore crudely analogous to Solar System formation. Pollack and Bodenheimer (1988) discuss in some detail the implications of this picture. Even if a disk origin is accepted, there are two distinct circumstances from which this disk arises. One scenario involves the formation of satellites from the material shed by a shrinking protoplanet. In this picture, proto-Jupiter once filled its Roche lobe, then shed mass and angular momentum as it cooled. An alternative view is an accretion disk which forms and evolves before Jupiter or Saturn approaches its final mass. In this picture, the disk serves a role more similar to that of the solar nebula, though with some important dynamical differences: it is more compact (because of tidal truncation) and it is evolving more rapidly relative to the accretion time (whereas the viscous evolution time and accretion time are roughly comparable in the solar nebula). The Solar System analogy must be used with care when applied to satellite systems! The choice between a disk that is shed and a true accretion disk has important implications for the chemistry (Stevenson 1988) but must be resolved by future dynamical modeling.

7. TEMPERATURES IN THE SOLAR NEBULA

Is there evidence in the outer Solar System for the expected temperature gradient of the solar nebula? Perhaps surprisingly, the answer is no. There is a trend of *decreasing* gas content in giant planets as one goes outward, but this surely reflects formation timescales and the ability of a proto-giant planet to accrete large amounts of gas before the onset of the T-Tauri phase. Satellite compositions seem to reflect more the immediate environment of the central planet than the background temperature of the nebula. The lack of CO in Titan and (presumably) Triton may reflect the processing of solar nebula CO into CH_4 in the disk or envelope surrounding the proto-giant planet, rather than any statement about solar nebula conditions. The only statement about temperature that seems reasonably firm is the placement of water condensation ($T \sim 160$ K) at around 5 AU at the time of condensate accumulation. There is not even clear evidence for a temperature gradient within the terrestrial planetary zone! The high density of Mercury is the only clear anomaly and is not readily explained by high temperature (it could, for example, be due to impact—see Benz, Slattery, and Cameron 1988).

Of course, absence of evidence is not the same as evidence of absence. Nevertheless, we have to admit that we know remarkably little about the temperature variation in the solar nebula, either spatially or with time.

8. GIANT PLANET FORMATION

The formation of the giant planets remains a major theoretical problem. Evidence presented above supports the idea that these planets may have formed by accumulating a core of ice and rock first, with gas accretion following—but truncated at some point, presumably because of the T–Tauri mass loss or perhaps (in Jupiter's case) by tidal truncation of the accretion zone (Lin and Papaloizou 1979). The problem lies in the accumulation of the rock–ice core on a sufficiently short timescale, so that the gas is still present. Conventional accumulation models, based on Safronov's theory (Safronov 1969) predict long timescales ($\gtrsim 10^7$ years), even with allowances for gas–drag effects (Hayashi, Nakazawa, and Nakagawa 1985). Rock–ice cores may begin to accumulate gas when they are only $\sim$ one Earth mass (Stevenson 1984b) and this aids the accumulation somewhat, but does not solve the problem. Lissauer (1987) pointed out that if the surface density of solids is sufficiently high in the region of Jupiter formation then a runaway accretion may take place, forming the necessary Jupiter core in $\sim 10^5$ years. The onset of ice condensation helps increase the surface density by a factor of three, but this may not be sufficient by itself. Stevenson and Lunine (1988) suggest that a further enhancement may arise because of a diffusive transport of water molecules from the terrestrial zone into the Jupiter formation region. This is illustrated schematically in Figure 4. Several criteria must be satisfied to make this work well and they may not all be met, but even a modest additional enhancement of the surface density in this region may make the mechanism work, at least to the extent of favoring the first (largest) giant planet at the water condensation front.

This suggests a speculative prediction for other planetary systems: Giant planets should occupy the region outward from the point of water condensation. The largest of these (the extrasolar equivalent of Jupiter) may be near the condensation point. This position will vary with the mass of the central star (or with the mass of the nebula that the star once had) but is presumably a calculable quantity as a function of star mass and angular momentum budget. We await the exciting prospect of identifying Jupiters and super-Jupiters about nearby stars, and characterizing their orbital distributions and properties.

9. CONCLUDING COMMENTS

There is great enthusiasm now for pursuing the identification of other planetary systems, but we should not forget that some aspects of our own system remain poorly understood yet crucial to the prediction and interpretation of extrasolar system observations. We would like to understand what lies beyond Pluto. Are there more planets? How are the comets distributed? Are there compositional *classes* of comets (in the same sense that they exist for asteroids)? We would also like to understand better the nature of primitive bodies within the currently known Solar System. Phoebe (the dark, presumably captured outer satellite of Saturn) is an example of a body that one would like to know better. We would like to have an improved understanding of planetary interiors because of the suspicion that they have "stored" information about the planetary accumulation. The Galileo mission may help here. We would like to define and quantify chemical processes in the outer nebula which may have modified the speciation away from that of the infalling interstellar gas. Shocks, photochemistry, lightning, and processing within the extended, tenuously bound atmospheres of protoplanets are examples of mechanisms for modifying the chemical speciation. Without a

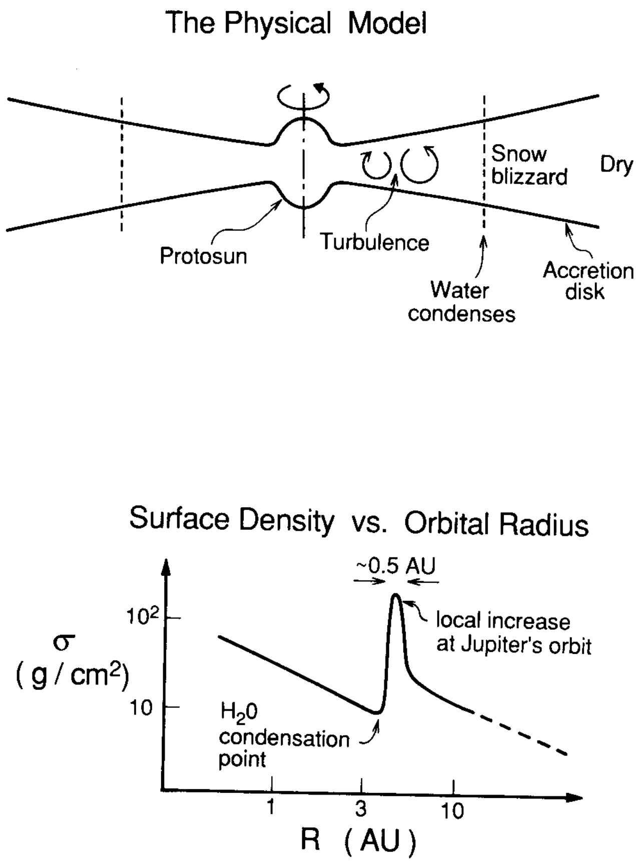

Figure 4. *A possible scenario for enhancing the water ice mass and surface density of solids in the vicinity of Jupiter formation (Stevenson and Lunine 1988).*

better understanding of our system, we may have difficulty extracting systematics from the expected and eagerly anticipated diversity of other systems whose discovery awaits in the next decade or two.

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DISCUSSION

B. Fegley: Dave, I agree with your conclusion that there is no evidence for a temperature gradient in the terrestrial planet region. However, the thing that concerns me is that if your model for drying out the inner nebula would change the ratio of carbon to oxygen in that region by as little as 40%, you would then obtain evidence for a temperature gradient in the inner region which we do not see. And it would lead to chemical fractionations which I do not believe we see. If you dry out the inner region of the nebula from which the terrestrial planets form, enough to change the C:O ratio in the gas from about 0.6 to a value of about 1, which is not that big a change, you would then lead to complete condensation of sulphur as refractory sulphite which would predict that Mercury contains a cosmic abundance of sulphur, and you would lead to formation of titanium nitride which would predict Mercury would contain 1% of the cosmic abundance of nitrogen. And you would also lead to the condensation of silicon carbide and graphite. And I don't believe that any of these trends are seen today in terrestrial planet compositions. So, at most, I think you only can dry out the inner nebula up to a point where you hit a C:O ratio of about 0.8 which is where you start making these unusual mineral assemblages which there seems to be no evidence for at all in the inner Solar System. And let me further point out that they do exist in the very small class of meteorites, the enstatite chondrites, which are difficult to explain but which by no means constitute a large fraction of chondrites.

Stevenson: OK. First point is that one does not need to dry out the inner nebula with high efficiency—especially in the innermost regions. The model would say that the most efficient drying is occuring in the most distant parts of inner nebula like say between 3 and 5 AU, or 2 and 5 AU, or something like that. And so one may not be necessarily changing the ratio of C:O in the region where you can do your chemical processing and condensation, like temperatures above 1200–1400 K. So, I accept your point as an interesting one which I had not thought about very much, but I am not sure that it's going to be a serious problem.

B. Fegley: Just one final comment: let me point out that meteoriticists currently believe that you have high temperatures at 3 AU to produce chondritic meteorites in this region of the nebula. And that they believe they need these high temperatures to produce refractory inclusions and chondrules. If that assertion of the meteoriticists is correct then you have these high temperatures at 3 AU and your mechanism would still produce a large amount of these unusual metal assemblages at that location, and would predict the enstatite chondrites would be the dominant class of the chondrites instead of being a minor class.

Stevenson: I think the important thing is not to think about 3 AU, 5 AU, whatever. The important thing is to think about temperature. If you have high temperatures at 3 AU presumably the water condensation is even further out. It would depend obviously on the time history and when this process is occuring compared to when those particular meteorite parent bodies are forming. I accept your point as a valid one that needs to be looked at further. But I don't, at least at the moment, see that as a serious problem.

H. Campins: I like your condensation limit, as a matter of fact, inspired by John Lewis. That has been an idea that we have been kicking around for a while to explain gassy versus dusty comets forming around that area. However, what kind of a demon would you then invoke to produce the turbulence?

Stevenson: I think that the re-distribution of water in the inner nebula might even be driven by the turbulence associated with disk accretion. The discussion this morning associated with Larson's paper dealt primarily with the stage after most of the accretion had taken place. But you can drive turbulence during the accretion itself, because of the angular momentum mismatch between the incoming material and the material already in the disk. I think, also, that you have to remember that even though Larson was talking about waves as a preference, in some cases waves will produce some mixing. Whether it will produce the amount of mixing that's needed for this model depends on the particular characteristics of those waves.

R. Terrile: Would you elaborate a little bit about the similarities between the embryonic cores of the outer planets? Specifically, people are concerned about what detection limits we need to really look for, if we are going to look for planets. And is a one Earth mass core large enough to initiate the accumulation of gas in the outer planets? And are the embryonic cores of Uranus and Neptune similar in mass to the embryonic cores of Jupiter and Saturn even though they are well mixed?

Stevenson: I think that it is possible that you could make a giant planet just with a one Earth mass core provided that one Earth mass core has water. It turns out that water is important because it affects the molecular weight of the envelope. And that is one of my major disagreements with some of the other published work. But, it does depend on exactly what the opacity is of the gas and if the gas is very opaque, if it has a lot of grains in it, then the critical mass for encouraging the gas to collapse on the core goes up. And it goes up to perhaps as much as 10 Earth masses if you go all the way to interstellar extinction opacity values. As to the similarities of the cores of the giant planets, one sees from an observational point of view that they are rather similar. I think of that as a statement about the total reservoir of solid material from which the planets formed. And therefore it is a statement about the surface density in the system rather than some other physical mechanism like when the instability occurred, or what was needed for runaway. It may be that those things are coincidental; it may be that it is the runaway that determines what the core mass is, but they do seem similar.

J. Lewis: I just want to say that if the degree of turbulence is severely sluggish, then one might see not an overall depletion of water in the inner part of the Solar System but instead a gradient of the mole fraction of water. And possibly one would see a significant difference in the behavior of carbon at that point in the asteriod belt where one sees from observation the onset of the enstatite chondrites.

Stevenson: Yes. That aspect I have thought about. I didn't talk about it here today. But, I've just written a paper dealing with the question of compositional gradients in the solar nebula. And the parameter that matters is the ratio of diffusivity to viscosity rather than the absolute value of either. And indeed one would expect in appropriate circumstances to have quite strong compositional gradients at certain places. And this might show up even in the asteroid belt or perhaps elsewhere. That bears looking at further.

C. Thompson: What are the main sources of uncertainty in the position of your water ice spike? What things do you have to choose, if any, in order to get it to the position to turn out right?

Stevenson: Well, of course, there is an arbitrariness in the model. You have to have a nebular model of some sort which makes a statement about how the temperature varies with radius. And traditionally that has been tied to alpha models of one sort or another. Even if you are heating the disk from the protosun, there will still be some temperature gradient. As to whether you can make the numbers work out right in the sense of having water ice condensation occur exactly the right place, I can't judge that aspect of the model. Maybe it works and maybe it doesn't. We simply don't know enough about the temperature conditions at 5 AU in the early Solar System.

R. Brown: You have emphasized how important the formation of the giant planet cores are to the scenario there, arriving at how they look today. And you also said how important the Epsilon ring data were in ruling out, for example, a strong layering of the interior of Uranus. Can you return to your cryptic comment about what Galileo might provide, presumably watching the evolution of its orbit, or finally understanding the interior mass distribution of Jupiter?

Stevenson: No. No. I meant the Galileo atmospheric probe. The probe is going to give us a much better number for helium. It turns out that, suprisingly enough, the helium abundance in the atmosphere of Jupiter is not as well known as for the other two that we have remote data for, namely Saturn and Uranus. And if you can tie that number down a bit better, you can make a better comparison among those planets. That is one thing. One would also hope—although as some of you no doubt know, it not clear that this will work—one also hopes that you will get a good water number. Whether we will really get the water abundance in the deep atmosphere of Jupiter from Galileo probe is questionable. But that would be the hope.

G. Wetherill: My question is about whether Jupiter's core is made by one big runaway, or is it by a series of small objects. You seem to think that maybe you can make it out of one Earth mass object. Without going into one great discussion, I have tried to do that and ran into horrible problems. Namely, that the escape velocity of these one Earth objects is comparable to the escape velocity of the Solar System. And you get an outer Solar System which is just a horrible mess of stuff in highly eccentric orbits. And it could well be that other Solar Systems are like that, but I don't think we live in one.

Stevenson: Well, OK, maybe I didn't make myself clear. During the process of runaway itself, there will be an earlier stage in the runaway where the objects have not yet reached ten Earth mass. There will be (I mean, you know how it works) prior to ten Earth mass, there may have been two 5 Earth mass objects or whatever and so on back in time. At the time that there were one Earth mass objects, you may already be accreting quite a bit of gas. And I'm concerned about the issue of what happens when those objects come together, because there will already be some mixing.

G. Wetherill: If they scatter each other, then you are in big trouble.

Stevenson: I fully understood that, and I didn't mean to imply that you want to do it by a Safronov type mechanism later on. I should point out though that it is still desirable to have some impacts later on to help with the obliquity issues.

G. Wetherill: Some, but the circular orbit of Neptune also, I think, argues against it.

Stevenson: Yes.

J. Lissauer: You made a point of the difference between the heat flows on Uranus and Neptune possibly indicating significant differences in internal structure.

Stevenson: Yes.

J. Lissauer: Now an idea that I heard many, many years ago was that these planets have very different heat flows, but they have very similar temperatures and the heat flow requires an adiabat. The adiabat is such that it is cool to this temperature of 57 degrees ...

Stevenson: That is right. Yes. I should have said that. That is primarily the work of Bill Hubbard; and it was a good idea and still a good idea except that quantitatively it doesn't work so well anymore because the heat flow for Uranus is even lower than people previously thought. And if you work through the models, you will find that it is an embarassment. If you just take a thermal evolution of Uranus and crank it through, you do not get as low a heat flow now as the upper bound says.

G. Wasserburg: OK. Time for a break.